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# Stress Corrosion Cracking and Hydrogen Embrittlement of High-Strength Fasteners


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Prepared by J. K. STANLEY
Materials Sciences Laboratory
Laboratory Operations

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Systems Engineering Operations
THE AEROSPACE CORPORATION

Prepared for SPACE AND MISSILE SYSTEMS ORGANIZATION
AIR FORCE SYSTEMS COMMAND
LOS ANGELES AIR FORCE STATION
Los Angeles, California

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THE AEROSPACE CORPORATION
El Segundo, California

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## FOREWORD

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Approved

W. C. Riley, Director
Materials Sciences Laboratory
Laboratory Operations

S. Lafazan, Group Director
Titan III Directorate
Vehicle Systems Division
Systems Engineering Operations

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Frank B. Alford, Jr., Col., USAF
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13 ABSTRACT

Unexpected, brittle failures of high-strength fasteners on aerospace vehicles have been caused by stress corrosion cracking (SCC) and by hydrogen stress cracking (HSC). Despite extensive study, much remains to be learned about the phenomena. The poorly understood failure mechanisms are difficult to differentiate, especially in the field. There is a growing use of the term SCC to describe failures by both mechanisms.

Data are given to characterize the classes. For low alloy carbon steels heat-treated to yield strengths below ~160 ksi, stress corrosion is not a problem, nor is hydrogen embrittlement (delayed cracking) very common. Above 160 ksi, difficulties can occur. The high-strength, precipitation-hardening, stainless steels have varying degrees of resistance to stress-corrosion cracking and hydrogen embrittlement, depending upon strength level and heat-treating procedures that influence the microstructure.

Consideration of plane strain fracture toughness $K_{IC}$ and stress corrosion threshold $K_{ISCC}$ parameters allows selection of optimum bolting materials for a specific environment. The advantage of plane strain fracture toughness analysis is that it does not differentiate between failure mechanisms; failure can be by either SCC or HSC.

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Distribution Statement (Continued)

Abstract (Continued)

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# I. INTRODUCTION

The design engineer may not always be fully aware of the possibility of brittle failures in fastener systems that could result from stress corrosion cracking (SCC) or hydrogen stress cracking (HSC).[1] The failure of high-strength fasteners in aerospace equipment as a result of SCC or HSC occurs infrequently and almost always unexpectedly. There is a growing acceptance of the term SCC to cover both mechanisms. The term 'environmental stress cracking' failures is also used sometimes.

Perhaps some of the reasons for occasional surprises from these phenomena are that (1) the existing knowledge was not available to the designer, (2) the possible hazard was recognized but ignored, (3) the existing knowledge was not believed applicable to the current situation, and (4) there was insufficient testing on a new material before it was commercialized. Designers should not design fasteners by handbook only. There are no reliable handbooks for material selection for possibly hazardous situations.

Very few fastener failures can be attributed to deficiencies in the technology of high-strength materials. Part of the difficulty can be traced to inadequate dissemination or utilization of available information and to the unrealistic assessments of technology by the improperly informed. Failures generally occur from inadequate knowledge of environmental conditions.

Any systems as sophisticated as those in aerospace application should use a fastener system to realize the full benefit of high-strength fasteners. A system requires proper material selection for bolt, washer, and nut. Bolt heads (hexagonal or 12-point), bolt-head fillets, and radii at base of threads are all important aspects of good bolt design. Care should be exercised in selection of nuts and washers. The use of washers produces more uniform loads. Nuts, if not properly selected, can fail by SCC or HSC.

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[1] HSC refers to hydrogen embrittlement, hydrogen cracking, and hydrogen-induced delayed cracking.

Little attention is presently given to torque-tension relationships in fastener systems, although an appreciation of this relationship is essential to optimum structural design, since the function of a fastener system is to furnish a clamping force or load. Optimum design requires torquing that will capitalize on the full strength potential of the bolt. Use of preload indicating devices and strain gages is often necessary, so that the loads placed on a bolt are known. Many engineers have no idea of the clamping forces in their structures. Effects of contact surface finish on components, coatings (if any), lubrication, asymmetrical holes, and torquing and retorquing on the same bolt are frequently not appreciated. When 70 to 80 percent of the energy of torquing is expended in overcoming friction on a dry bolt-nut combination, little energy is available to develop a clamping force.

Fatigue of the fasteners in aerospace hardware has not been a problem, mainly because acceptance testing time and flight times have been too short (less than 1 hr) to develop failures with the stress loadings. However, on the space shuttle that aims for 100 flights, fatigue of fasteners could become a problem. As parts subjected to higher stress are used, more attention must be given to steel cleanliness (inclusions act as crack nuclei), to radiused threads (to reduce notch effect), and to larger head shank fillets (also to reduce notch effect). High-strength fasteners should have threads and head shank fillets rolled on after heat treatment, and shanks should be ground and polished. Rolling threads after heat treatment builds up a residual stress to counteract a portion of the applied tensile load, and it ensures unbroken grain flow lines through the critical area created by the notch effect of the threads. Hood (Ref. 1) reports experiments in which the threads and fillets were rolled before and after heat treatment. The 260 ksi (UTS) bolt rolled before heat treatment had a time to failure in SCC of 2 hr, whereas if the threads and fillets were rolled after heat treatment, the bolt had a time to failure of 74 hr.

The incidence of fastener failure has been decreasing because engineers have learned to avoid materials that have given difficulties in the past. Solutions are not always as simple as a material substitution, but may be complex, involving material changes, use of coatings, redesign, or reduction of stress, or a

combination of these (Ref. 2). There are, of course, many other types of fastener failures, e.g., overtorquing and stress-rupture, but failures as a result of stress-corrosion or hydrogen embrittlement are most insidious.

Because of a lack of standardized test methods for SCC and for HSC, statistical analyses of data are not feasible. ASTM is actively working in both areas to develop standardized tests for both phenomena.[2]

As the strength level increases above ~160 ksi, both the sensitivity to brittle fracture and the susceptibility to SCC and HSC increase. Although steels with strengths in excess of 300 ksi are available, designers are reluctant to push for this strength level and have settled on levels of 200 to 260 ksi. Some designers who have experienced either SCC or HSC have even backed off to strengths of 160 to 180 ksi.

SCC and HSC have caused many serious and unexpected failures in high-strength fasteners. Failures have occurred in applications at stresses that appeared safe (below the yield strength) from stress analyses, even with the use of generous factors of safety. These failures have led designers to use materials far below their true capabilities, either by using less than optimum strengths of a high-strength steel or by using steels heat-treated to the maximum strength at very low strength levels, say 25 percent of the yield strength.

Both SCC and HSC involve chemical and metallurgical factors that are poorly understood. Much research has been done in various environments to establish relative sensitivity of materials to these two mechanisms. Media are often chosen to give accelerated failure. Metallurgical structures have been studied extensively so that crack initiation and propagation could be better understood. So far, this approach has not been particularly fruitful.

Some of the difficulty in understanding the two fracture modes arises because they are so much alike. Hydrogen appears to be the culprit in both phenomena. It is only in the laboratory, by electrochemical means, that the

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[2] The American Society for Testing and Materials is seeking to develop test procedures in the areas of stress corrosion cracking and corrosion fatigue, smooth test specimens, environments and materials, precrack growth, subcritical crack growth, and hydrogen embrittlement.

two mechanisms can be uniquely differentiated. In the field, it is difficult, if not impossible, to identify which cracking phenomenon was responsible for the failure. Stress-corrosion theory is not sufficiently advanced to predict failure times. There is a need for a unifying theoretical mechanism for explanation of SCC and HSC.

However, despite many similarities, the basic mechanisms are different. Although brittle failure in high-strength steels exposed to aqueous environments has been well documented, there is still controversy concerning the mechanisms of delayed failure. Reference 3 contains a useful discussion of the mechanisms of failure in SCC.

Shotpeening, plating, and painting of low alloy, high-strength martensitic fasteners as a means of preventing delayed failures at ambient temperatures has been largely unsatisfactory. Current interest lies in use of HSC- or SCC-resistant stainless types and superalloys (nickel-base and cobalt-base).

Which of these two mechanisms is responsible for failure of a metal fastener is generally of academic interest to the engineer. Because HSC and SCC are so similar, the same type of solution will often suffice for both problems.

## II. DEFINITION AND DIFFERENTIATION OF STRESS CORROSION CRACKING AND HYDROGEN STRESS CRACKING

Excellent reviews of SCC and HSC are to be found in Refs. 4 and 5.

Stress corrosion cracking is nucleation of a crack in a susceptible metal in a corrosive environment while the metal is stressed in tension; the crack then propagates by stress-induced corrosion of the advancing crack tip. Cracking may occur intergranularly or transgranularly, depending on the metal and its heat treatment. Failure occurs with little or no plastic deformation, the fractures are termed brittle failures. The stresses are generally below the yield stress.

The SCC occurs in specific environments and with environmentally sensitive metals. In most cases, there is negligible loss of metal by general corrosion, and at times the corrosion is imperceptible to the eye. Stress corrosion cracking requires highly anodic areas and a localized pH, such as may exist in oxide film cracks, pits, crevices, and cold-worked areas.

HSC occurs because of hydrogen penetration into the lattice in the presence of a tensile stress. It is generally agreed that corrosion plays no direct role in this mechanism. However, corrosion often plays an indirect role as the source of hydrogen.

In classic HSC, the hydrogen is introduced into solid solution by electrolytic charging, pickling, heat treatment, and corrosion reactions. Hydrogen then causes delayed failure under static load in high-strength alloys, and the embrittling effect increases with increase in severity of notch, i.e., stress concentration (Refs. 6 and 7). Tests for HSC have not been standardized; they should include both machine-notched and precracked specimens.

Obviously, if no hydrogen is present in the lattice, no HSC can occur. If hydrogen has entered during pickling, heat treating, or electroplating and is removed by baking in air or vacuum, no HSC will occur when tensile stresses are applied. The amount of hydrogen that will cause HSC is exceedingly small, of the order of 4 or 5 ppm. Damage has been reported with hydrogen contents

or even less than 1 ppm (Ref. 4). The work of Mazanec and Sejnoha (Ref. 8) suggests that delayed fractures in as-quenched steels are due to some properties of the martensite transformation itself and not to hydrogen. Defects in the austenite grain boundary occur as a result of dynamic effects caused by growing martensite plates. These defects are a source of weakness in the prior austenite grain boundaries and give rise to delayed fracture.

The delayed failure characteristics of 4340 steel, which was exposed to distilled water and failed presumably by HSC, are shown in Figure 1. (Nominal compositions of all alloys mentioned in this report are given in Table 1.) Similar failure characteristics are caused by SCC. Note in Figure 1 the short time to failure of the 4340 as the ultimate tensile strength (UTS) of the steel increases and the threshold stresses below which no failure occurs (Ref. 7).

The important parameters in these delayed failures are strength levels, steel composition and metallurgical structure (microstructure), tensile stresses, environment (i.e., tendency toward corrosion or introduction of hydrogen), and time. Increases in temperature seem to increase the likelihood of SCC more than that of HSC, the latter occurs around room temperature. The tensile stresses can be applied stresses, residual stresses (as in roll-formed threads, heat treatment, welding, straightening, or cold-rolling), or a sum of these stresses. If residual stresses are present, they are very difficult to measure or estimate so that one does not know their magnitudes. For either SCC or HSC, there exists a threshold limit below which the stresses will not cause fracture.

In the laboratory, the electrochemical behavior of the metal offers perhaps the best arguments that SSC and HSC are separate, distinct phenomena. Delayed cracking that occurs under cathodic polarization (hydrogen polarization) can hardly be attributed to SCC. Conversely, delayed fracturing where anodic polarization is causing dissolution (corrosion) of the metal can hardly be identified as HSC. The polarization vs time to failure curves identify the two mechanisms uniquely. Obviously, such methods would have limited field use. Brown (Ref. 9) and Bhatt and Phelps (Ref. 10) have proposed this type of electrochemical procedure for distinguishing between SCC and HSC. SCC occurs by definition when cracking involves corrosion at anodic areas of the advancing tip

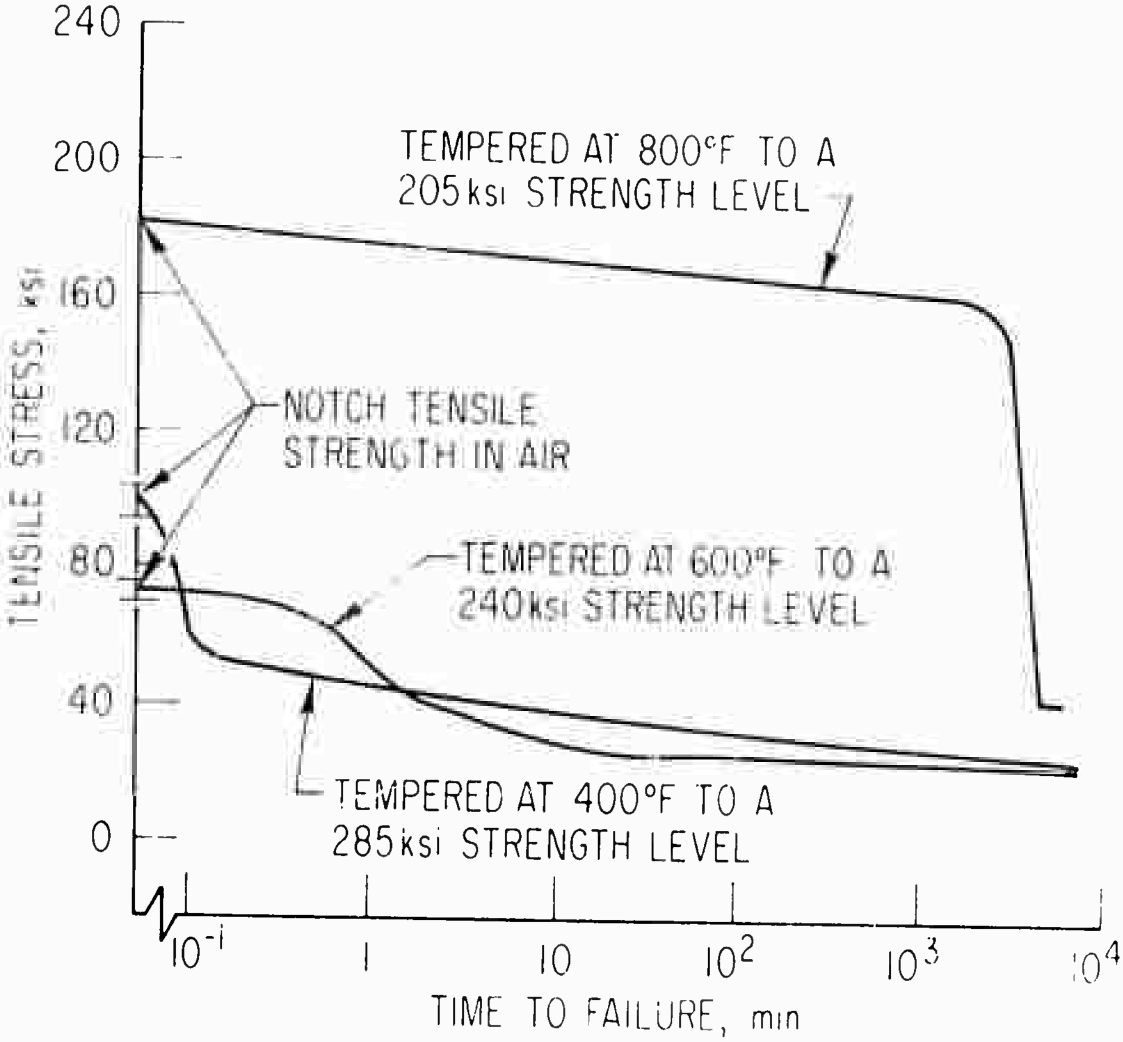


Figure 1. Delayed Failure Characteristics of 4340 Steel at Various Strength Levels Resulting from Exposure to Distilled Water at 68 F (Ref. 7)

Table 1. Nominal Compositions of All Alloys Mentioned in the Text

| Material | Elements | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | Cr | Ni | Co | Fe | Mo | W | Cb | Ti | Al | Other |
| [illegible] | [illegible] | [illegible] | | | bal | [illegible] | | | | | |
| 4140 | [illegible] | [illegible] | | | bal | [illegible] | | | | | |
| 4340 | [illegible] | [illegible] | [illegible] | | bal | [illegible] | | | | | |
| [illegible] | [illegible] | | [illegible] | | bal | [illegible] | | | | | |
| HY-TUF | [illegible] | [illegible] | [illegible] | | bal | [illegible] | | | | | [illegible] Si |
| D6AC | 0,45 | 1,00 | [illegible] | | bal | [illegible] | | | | | [illegible] V |
| HP 9-4-[illegible] | [illegible] | [illegible] | [illegible] | [illegible] | bal | [illegible] | | | | | |
| Maraging 200 | [illegible] | | [illegible] | [illegible] | bal | [illegible] | | | [illegible] | 0,10 | |
| Maraging [illegible] | 0,03 | | [illegible] | [illegible] | bal | 4,80 | | | 0,40 | 0,10 | |
| Maraging [illegible] | 0,03 | | [illegible] | [illegible] | bal | [illegible] | | | 0,60 | [illegible] | |
| Type 410 | [illegible] | [illegible] | | | bal | | | | | | |
| Type [illegible] | [illegible] | [illegible] | | | bal | [illegible] | | | | | |
| Type 422 | [illegible] | [illegible] | [illegible] | | bal | 1,00 | [illegible] | | | | [illegible] V |
| Type 431 | [illegible] | [illegible] | 1,8 | | bal | | | | | | |
| Type 440C | 1,10 | [illegible] | [illegible] | | bal | [illegible] | | | | | |
| H-11 | [illegible] | [illegible] | | | bal | [illegible] | | | | | [illegible] V |
| 17-4 PH | 0,07 | 16,50 | 4,0 | | bal | | | 0,3 | | | 0,4 Cu |
| 17-7 PH | [illegible] | 17,00 | 7,1 | | bal | | | | | 1,10 | |
| PH 15-7 Mo | [illegible] | 15,0 | 12,1 | | bal | 2,50 | | | | 1,10 | |
| PH 13-8 Mo | 0,05 | 12,75 | 8,0 | | bal | 2,25 | | | | | |
| PH 14-8 Mo | 0,05 | 14,35 | 8,1 | | bal | [illegible] | | | | 1,10 | |
| 15-5 PH | 0,07 | 14,75 | 4,5 | | bal | | | 0,3 | | | 0,35 Cu |
| AM 350 | 0,10 | 16,5 | 4,5 | | bal | 2,9 | | | | | 0,1 N |
| AM 355 | 0,12 | [illegible] | 4,5 | | bal | 2,9 | | | | | 0,1 N |
| A [illegible] | 0,03 | 14,5 | [illegible] | | bal | | | | 0,80 | | |
| Inconel 718 | 0,05 | 15,0 | 26,0 | | bal | 1,25 | | | 2,15 | 0,2 | 0,3 V |
| Haynes 25 (L605, WF-11) | 0,10 | 20,0 | 10,0 | bal | | | 15,0 | | | | |
| Custom 455 | [illegible] | 11,75 | 8,5 | | bal | 0,5 | | 0,3 | 1,1 | | 2,0 Cu |
| A 286 | 0,05 | 14,75 | [illegible] | | bal | 1,3 | | | 2,15 | 0,15 | 0,3 V |
| MP 35N | | 20,0 | 35,0 | 35,0 | | 10,0 | | | | | |
| Hastelloy X | 0,10 | 22,0 | bal | 1,5 | 18,5 | [illegible] | 0,6 | | | | |
| Rene 41 | [illegible] | 19,0 | bal | 11,0 | 10,0 | | | | 3,1 | 1,5 | |
| Waspaloy | 0,07 | 19,5 | bal | 13,5 | 2,0 | 4,3 | | | 2,5 | 0,7 | |
| Inconel X750 | 0,04 | [illegible] | bal | | 7,0 | | | 0,95 | 2,5 | 0,7 | |
| Type 303 | 0,15 | 18,0 | 9,0 | | bal | | | | | | |
| Type 304 | 0,08 | 18,5 | 9,5 | | bal | | | | | | |
| Type 309 | 0,20 | 23,0 | 13,5 | | bal | | | | | | |
| Type 316 | 0,08 | 17,0 | 12,0 | | bal | 2,25 | | | | | |
| Type 321 | 0,08 | 18,0 | 11,0 | | bal | | | | 5×C | | |
| Type 347 | 0,08 | 18,0 | 11,0 | | bal | | | 10×C | | | |
| Unitemp 212 | 0,08 | 16,0 | 25,0 | | bal | | | 0,50 | 4,0 | 0,15 | |

(Ref. 11). HSC by definition is cracking induced by hydrogen generation at the tip by cathodic currents. Differences that have been generally noted in failures due to HSC or SCC are given in Table 2.

Many test procedures are used to evaluate susceptibility to SCC and HSC. A common SCC test to establish susceptibility of bar stock involves loading the specimen to some high percentage of its yield stress, or sometimes UTS, and exposing it to alternate immersion in a 3.5 percent NaCl solution for 10 min and drying in forced air for 50 min. The cycling is continued until the specimen fails or the test is discontinued. The sodium chloride is usually dissolved in distilled water or is acidified (to pH of ~1.5). Imposed stresses generally vary from 75 to 90 percent of the tensile strength of fatigue-cracked notched specimens and from 75 to 90 percent of the 0.2 percent yield strengths of unnotched specimens.

Austenitic steels are commonly checked for SCC by exposure to 42 percent boiling aqueous $MgCl_2$ (154C, 309F) solution; ferritic stainless steels, by contrast, are relatively immune to cracking in $MgCl_2$ (Ref. 12).

Until recently, SCC tests were conducted on smooth specimens. These tests are helpful in selection of materials for environments or in development of coatings. They could not be used, however, for establishing safe design loads. Often there is large scatter in the data. The SCC tests on both smooth and precracked specimens used in fracture toughness studies provide the designer with tools for material selection on the basis of service environments that can be simulated in the laboratory. The testing methods, however, need standardization.

For the HSC test to establish susceptibility, a notched specimen is loaded to 75 percent or more of its notched yield strength, and hydrogen is cathodically charged into the steel while it is under load. Sometimes a notched specimen is plated with electrolytic cadmium and then loaded. A notched specimen is more susceptible to HSC than an unnotched one. Cathodically charging a steel with hydrogen provides considerably more hydrogen than is necessary to produce a delayed failure. Loadings are similar to those used for SCC tests.

Table 2. Differences in Failures by HSC and SCC

| HSC | SCC |
|---|---|
| Rupture nucleation inside the metal or at notches | Rupture nucleation at the metal-environment interface originating from pits |
| Single crack with minimal branching | Extensive branching and several secondary cracks |
| Electron microscopy may show striations indicative of discontinuous crack propagation. (Do not confuse with fatigue striations.) | No striations are observable on the fracture face |
| Presence of flat dimples and hairline lattices on the grains, as seen by electron microscopy | Flat dimples and hairlines on grains are less numerous than in HSC, as seen by electron microscopy |
| No corrosion is ordinarily present | Corrosion products are evident by microscopy |
| Occurs mainly in martensitic steels at very high ultimate strength levels | Occurs in many alloys (ferritic, austenitic, martensitic) over a wide range of UTS levels |

High-strength bolts must also pass a stress-durability (static fatigue) test. The bolts are stressed to 75 percent of the minimum tensile load and are held for 96 hr. If embrittled by hydrogen, they will fail.

The potentiostatic procedure is becoming more popular for the study of both SCC and HSC. Figure 2 shows that 13-8PH steel can be made to fail by either phenomenon if the potential is changed (Ref. 13). This type of test can probably be standardized to assess the relative susceptibility of a given steel in various heat-treated conditions to either SCC or HSC. The test is definitely a laboratory tool and would yield guidelines rather than design data.

In environmental cracking failures at the launch ranges, it is not possible to unequivocally separate HSC from SCC. Therefore, the failures are often attributed to (1) stress-corrosion cracking (which includes SCC and HSC) or (2) environmental stress cracking. For engineering purposes, this may be sufficient. Pinpointing the actual failure mechanism may be of academic interest only.

Electron fractography with the transmission electron microscope or the newer scanning electron microscope cannot uniquely identify HSC. Electron microscopy is a very useful tool when used in conjunction with other tools. A knowledge of circumstances leading to failure is a valuable adjunct to successful failure analyses. The compilations of electron fractographs by AFML are helpful in deciding what the nature of the failure mode may be (Ref. 14).

Intergranular and transgranular cracking result from hydrogen, a susceptible microstructure, the specimen geometry, and static or dynamic tensile loading. It is not true that intergranular cracking is typical of SCC and that transgranular cracking is characteristic of HSC. A review (Ref. 15) of 39 studies involving fractography of materials failed by HSC and SCC found 23 instances of fully or predominantly intergranular cracks, 8 instances of fully or predominantly transgranular cracks, and 8 mixed cases. Intergranular cracking appears to be the most frequent type in both HSC and SCC.

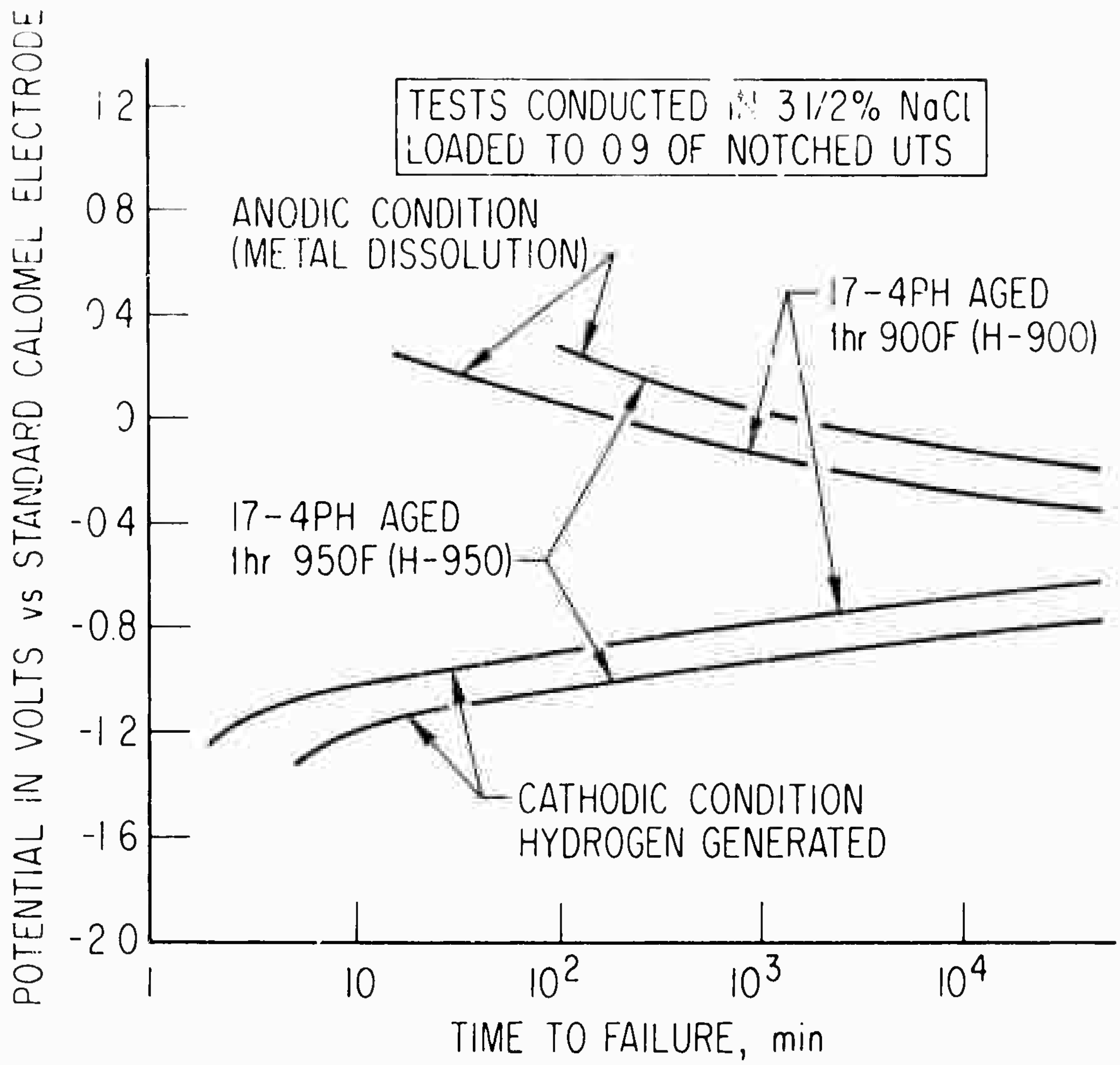


Figure 2. Typical Data Obtained from Potentiostatic Tests (Ref. 13)

## III. MATERIALS FOR HIGH STRENGTH FASTENERS

The aerospace industry has emphasized the systems concept of fasteners for the sake of reliability. Design has been improved so that stronger, lighter, and more sophisticated fastener systems are available. Environmentally resistant fasteners have recently been studied.

Steel composition is important, as is the metallurgical structure. The time for initiation of the first crack in either HSC or SCC depends on the microstructure resistance to hydrogen diffusion or pit corrosion.

Much is known empirically about what compositions and structures are susceptible to HSC or SCC, but little is known from first principles about the relation of microstructure to crack initiation and propagation. Most data are basically phenomenological. Tiner and Galpin (Reference 16) are among the few to attempt studies of microprocesses involved in SCC.

Nuts and washers must also be carefully selected for the fastener system. Careful selection means that the nuts are also subjected to a SCC test, generally torqued on a bolt and submerged in salt water. Washers are used to distribute the load. They too should be compatible with the bolts so that they do not produce galvanic corrosion. Because they are loaded in compression, they do not fail by HSC or SCC.

Materials for aerospace fasteners are categorized in several ways: (1) by strength levels, (2) by composition and metallographic structure, and (3) by relative susceptibility to SCC and HSC. In the future, the steels will be categorized by fracture toughness parameters; some such compilations are already appearing and are discussed in Section V.

### A. CLASSIFICATION BY STRENGTH LEVEL

One arbitrary classification of threaded fasteners is by ultimate strength range:

| | |
|---|---|
| low strength | < 125 ksi |
| medium strength | 125-160 ksi |

| | |
|---|---|
| high strength | 180-260 ksi |
| ultra-high strength | >280 ksi |

Figure 3 shows the strength ranges for some popular alloy steel fasteners. Figure 4 shows the strength ranges for some stainless steels and superalloys.

Of course, strength levels disclose neither the type, composition, and microstructure of the materials nor susceptibility to SCC and HSC.

## B. CLASSIFICATION BY COMPOSITION AND METALLURGICAL STRUCTURE

Another classification, by type of alloy, is useful to the understanding of the behavior of these materials; alloys are

martensitic,

stainless steels (austenitic and ferritic),

precipitation-hardening stainless steels
(semi-austenitic and martensitic), or

superalloys (nickel-base and cobalt-base)

Experience has shown that some types of high-strength steels are quite susceptible to SCC and HSC while others are not. Some change in degree of susceptibility to SCC results from the precipitation of grain boundary carbides and the presence of secondary phases. Corrosion theory is not sophisticated enough to explain this phenomenon.

Steels used at or above 160 ksi UTS should meet AMS-2300A cleanliness standards. Steels should be vacuum- or consumable arc-melted for minimization of inclusions, which can cause pitting. Mechanical properties sometimes can be higher and more uniform with greater toughness if steels are vacuum melted.

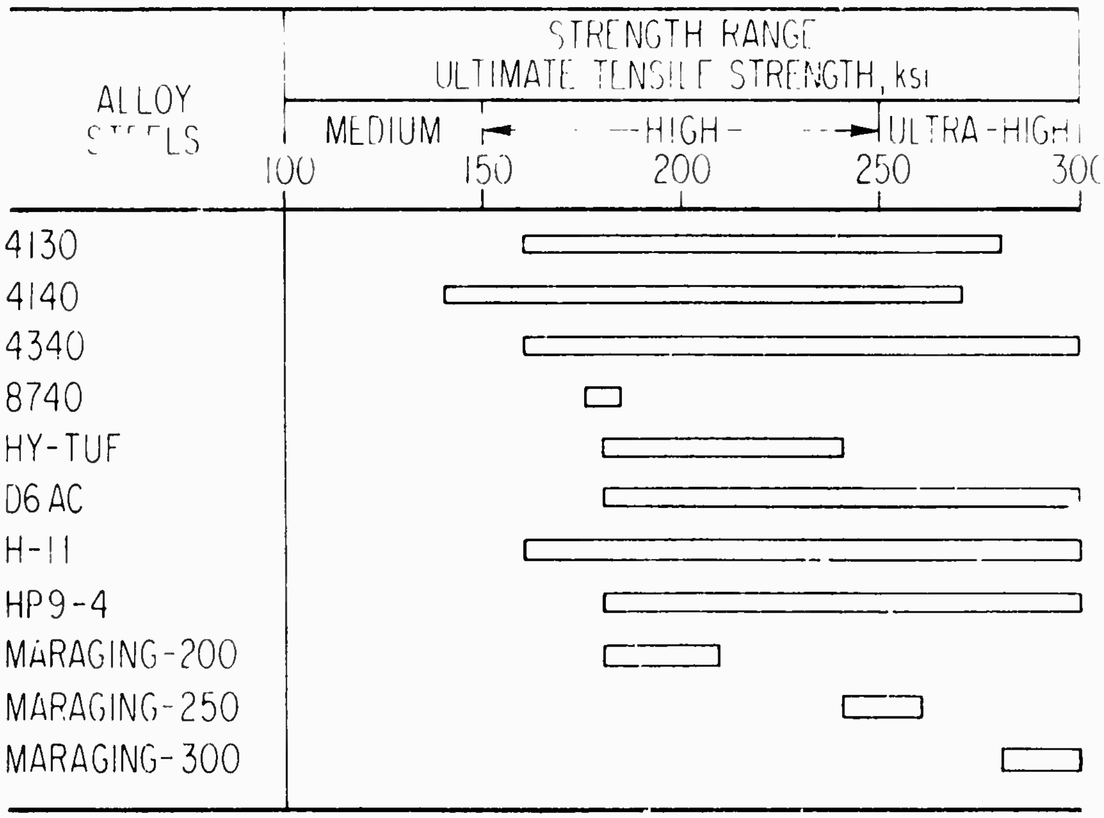


Figure 3. Classification of Low Alloy Steels (Martensitic Types) by Strength Range

(The wide ranges of strength of some of the steels are obtained by tempering at different temperatures.)

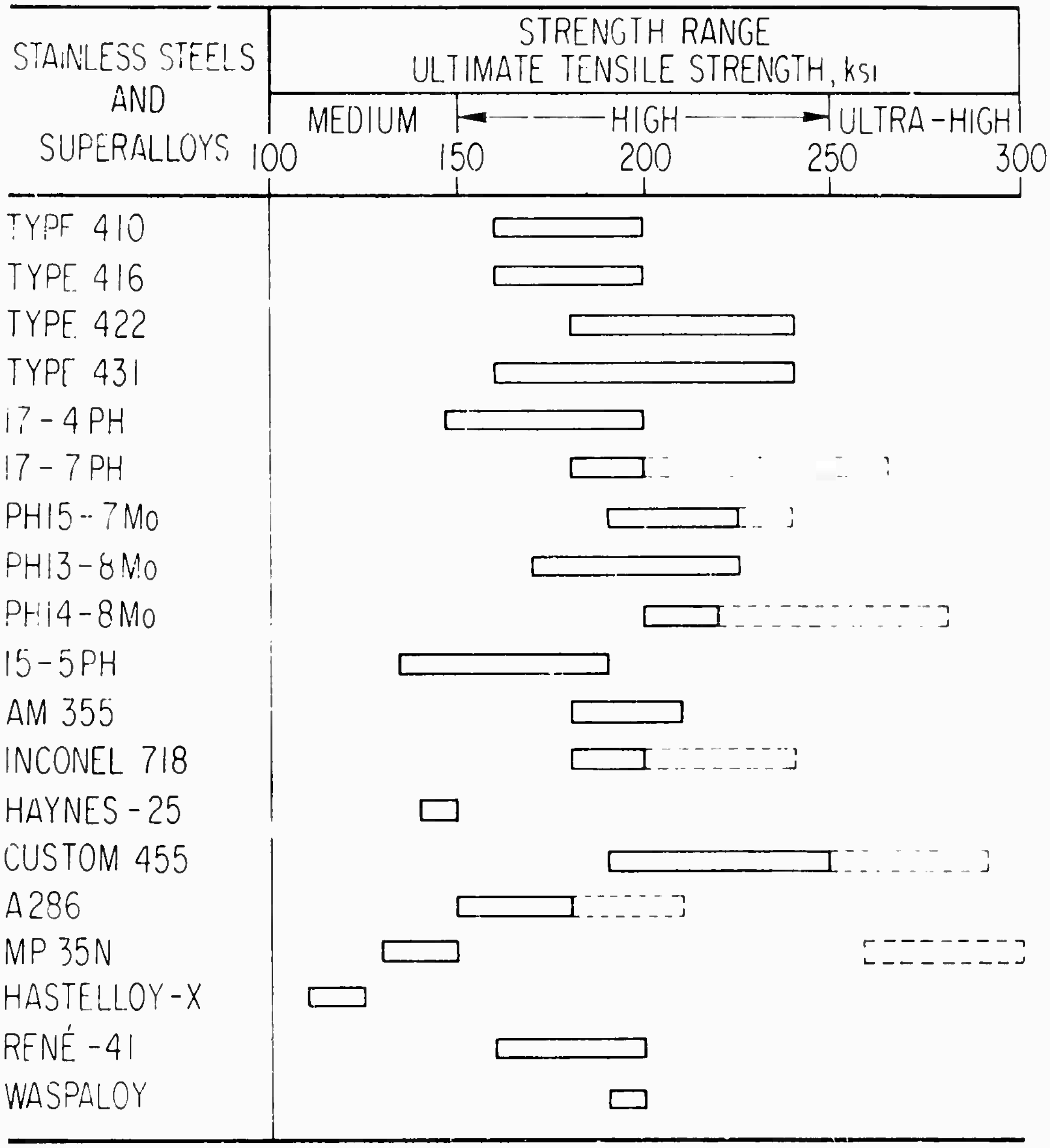


Figure 4. Classification of Stainless Steels and Superalloys by Strength Range

(Dashed lines indicate strengths obtainable by cold-work and aging.)

## C. MARTENSITIC STEELS

For carbon and low alloy steels heat-treated to strength levels of ≤ 160 ksi, SCC is not a problem nor is HSC common. In the martensitic steels, there is a ductile-to-brittle transition range, and crack growth takes place differently above and below the range. Above the transition, environmentally induced slow crack growth occurs over a large area before catastrophic failure occurs. Below the transition, significantly less crack growth is observed before total failure occurs. Below the transition, a martensitic steel has poor impact or impact-tension properties. Fasteners made of H-11 steel heat-treated to ~200 ksi are usable to -65°F before the transition is reached.

The austenitic-type stainless steels and nickel-base alloys (Inconel 718, Waspaloy, A286, and MP 35N) have no such transition and actually have enhanced mechanical properties at cryogenic temperatures.

In martensitic steels, the prior austenite grain boundaries appear to facilitate hydrogen diffusion. It is probably true that all martensitic steels will fail by HSC under severe conditions. Retained austenite facilitates susceptibility to SCC (Ref. 17).

The maraging steels can develop strengths > 300,000 psi; thus far they have had limited application at this level, but at lower strengths they are usable alloys. These steels are cooled from the austenitizing temperature to form a soft and weak martensite, which is hardened and strengthened by aging at 850-950°F. The fracture toughness of these materials is good up to yield strengths of ~250 ksi.

## D. STAINLESS STEELS (AUSTENITIC AND FERRITIC)

The austenitic steels of the Type 300 series are much too weak[3] to be considered for use in high-strength fasteners. Only through cold work and

[3] MIL Handbook 5A assigns Types 301, 302, 303, 304, 316, 321, and 347 yield strengths of 30 ksi and ultimate tensile strengths of 75 ksi.

stress relief can high strengths be developed in these materials; half-hard materials have a UTS of 150 ksi, while fully hard materials have a UTS of 185 ksi.

Even though the annealed materials have low strength levels, the alloys can be fractured in environments containing chlorides. Suss (Ref. 17) reports SCC failures with stresses as low as 2000 psi in an environment of 50 ppm sodium chloride. The annealed materials are very resistant to HSC. Pitting on these steels can occur at emergent slip lines as well as at inclusions.

Precipitation-hardened austenitic nickel chromium is also available. Alloy A286, one of the first, is now one of the most popular high-strength stainless steels. If the alloy is cold-worked (60%) and aged (1200°F), strengths $>$200 ksi are attainable. Alloy A286 has outstanding resistance to SCC and HSC. In potentiostatic experiments at The Aerospace Corp. Material Sciences Laboratory, it has been impossible to fracture the alloy under anodic or cathodic conditions. Field experience confirms the alloy's high resistance to these phenomena.

Ferrite in an austenitic steel (Type 304) retards SCC that may have originated in the austenite. Type 301, when cold-worked over 20%, shows marked susceptibility to HSC because of the martensite formed from the austenite by cold work (Ref. 12). Stainless steels containing a mixture of austenite and martensite may fail by either HSC or SCC, depending on the environment. Additions of silicon to austenitic steels in concentrations $\leq$ 5 percent are claimed to make the steels immune to SCC (Ref. 18).

The ferritic stainless steels, Type 400 (e.g., 410, 416, 420, 422, and 431), are heat-treatable to strengths of $\sim$200 ksi. Although these steels are martensitic in structure, they are not generally considered in the martensitic class because they have relatively high chromium contents, $\sim$13 percent. These types have good general corrosion resistance but they are susceptible to SCC. This susceptibility can be removed by tempering at 1100°F or higher, but high strength is sacrificed (Ref. 19). Reference 20 recommends limiting the use of 13 percent chromium in corrosive service to $\sim$140 ksi.

Failure of the ferritic stainless steels by SCC is intergranular or transgranular, depending on the tempering temperature (Refs. 21 and 22). When cracking is intergranular, the fracture follows the prior austenite grain boundaries (Ref. 16). The high susceptibility to cracking in the prior austenite grain boundary is ascribed to the presence of ε-carbide. Delta ferrite, sometimes present in Type 410, increases susceptibility to SCC (Ref. 17).

The 13 percent chromium martensitic stainless steels, when tempered in their secondary hardening range, have minimum resistance to SCC or HSC (Ref. 23). Phelps and Loginow (Ref. 24) have shown that a 13 percent chromium steel, when tempered above 900° F, has a minimum time to failure in the Kure (N. Carolina) Beach atmosphere.

## E. PRECIPITATION-HARDENING STAINLESS STEELS

The precipitation-hardening stainless steels offer high-strength, unplated, corrosion-resistant alloys that can resist HSC and SCC, which have been experienced with plated and unplated martensitic, low- and high-alloy steels in the range from 200 to 250 ksi.

These precipitation-hardening steels have varying degrees of resistance to SCC and HSC depending, of course, on strength level but also on the temperature of the aging treatment. Aging below 1000° F may make these steels susceptible to SCC and HSC, but aging above this temperature makes them very resistant to these cracking phenomena. The reasons for this behavior are not well understood.

The precipitation-hardening steels are of two basic classes, martensitic and semi-austenitic. The martensitic types are 17-4 PH, 15-5 PH, and PH 13-8 Mo. In these alloys, the martensitic structure forms upon cooling from a solution treatment; subsequent aging between 900 and 1150° F strengthens the martensite by precipitation hardening and tempering. Typical semi-austenitic steels are 17-7 PH, PH 15-7 Mo, PH 14-8 Mo, and AM 350. In these alloys, the composition has been adjusted so that the

austenite forms upon solution treatment and is retained at room temperature. In this condition it is readily fabricated (cold-worked). The hardening is obtained by reheating the austenite to 1400 or 1750°F (called conditioning), cooling, and finally aging at 950 or 1050°F.

If either of these steels is overaged beyond highest strength, both the fracture toughness and the SCC resistance are improved.

The fracture toughness and SCC resistance of martensitic steels are significantly higher than those of the semi-austenitic types, probably because of the absence of delta ferritic and grain-boundary carbides (Ref. 25).

## F. SUPERALLOYS (NICKEL-BASE AND COBALT-BASE)

In general, the greater the nickel content in the austenitic steels, the greater their resistance to SCC and to HSC.

Ultra-high-strength stainless fasteners are made from superalloys (high-strength nickel-base and cobalt-base alloys). The nickel-base Inco 718 superalloy, cold-worked and precipitation-hardened, has strengths in excess of 200,000 psi.

The new and highly alloyed MP-35N exhibits the corrosion resistance of the best nickel-base alloys. It is highly resistant to SCC and to HSC in salt environments and marine atmospheres. It is a fairly new material, and little experience with it has been obtained.

## G. CLASSIFICATION BY RELATIVE RESISTANCE TO SCC

A third classification (Ref. 26) rates materials according to relative susceptibility to SCC and can be used as a rough guide to material selection based on experience and some laboratory work. This classification comprises (1) alloys and heat treatments that can be used without restriction, (2) alloys and heat treatments that must be used with caution, and (3) alloys and heat treatments that should not be used.

These materials are described in Tables 3-5. The tables apply only to SCC in environments of sodium chloride solutions, salt sprays, alternate immersion (wetting and drying), and marine atmospheres. Similar tables for HSC are not available.

These ratings are not to be construed as exact, because no attempt has been made to evaluate the effects of stress, environment, metallographic structure, and time. These tables represent the type of SCC data that was available before the advent of fracture mechanics. No attempt has been made here to incorporate data obtained by fracture mechanics and given elsewhere. Other factors of concern to the aerospace materials engineer are the metal-propellant compatibilities, which are not discussed here.

Table 3. Materials Highly Resistant to SCC

| Materials | Type | Heat Treatment[a] | Remarks |
|---|---|---|---|
| 300 series stainless types 303, 304, 316, 321, 347 | Austenitic | Annealing | Stressed material can crack in chloride solutions. Annealed materials are not of high strength. Cold-worked materials can develop high strength but they must be stress-relieved. |
| 17-4 PH | Martensitic | H1000 and above | |
| 17-7 PH | Semi-austenitic | CH 900 | Strength is developed by cold-working (60%) and aging (900° F). |
| PH 13-8 Mo | Martensitic | H1000 and above | |
| 15-5 PH | Martensitic | H1000 and above | |
| PH 15-7 Mo | Semi-austenitic | CH 900 | Strength is developed by cold-working (60%) and aging (900° F). |
| PH 14-8 Mo | Semi-austenitic | CH 900 | Same as PH 15-7 Mo. |
| AM 350 | Semi-austenitic | SCT1000 and above | |
| AM 355 | Semi-austenitic | SCT1000 and above | |
| Custom-455 | Semi-austenitic | H1000 and above | |
| A 286 | Austenitic | Solution-treated and aged | |
| A 286 (CW and Aged) | Austenitic | | High strength is developed by cold-working (60%) and aging (1200° F). |
| Inconel 718 | Face-centered cubic | Solution-treated and aged | |
| Inconel X-750 | Face-centered cubic | Solution-treated and aged | |
| Rene-41 | Face-centered cubic | Solution-treated and aged | |
| MP 35N | Face-centered cubic | Solution-treated and aged | Solution-annealed, cold-worked 60%, and aged. |
| Waspaloy | Face-centered | Solution-treated and aged | |
| Low Alloy Steels 4130, 4140, 4340, 8740 | Martensitic | Quenched and tempered | High resistance to SCC if tempered to 160 ksi or lower. |
| Maraging Steel | Martensitic | Solution-treated and aged | High resistance if heat-treated to 200 ksi or lower. |

[a]For heat treatments, refer to Aerospace Structural Metals Handbook, Metals Handbook ASM, or steel producer's literature.

Table 4. Materials Highly Resistant to SCC if Used with Caution

| Materials | Type | Heat Treatment | Remarks |
|---|---|---|---|
| Low-alloy steels 4130, 4140, 4340, 8740, D6AC, HY-TUF | Martensitic | Quenched and tempered | Good resistance to SCC if tempered to ~ 160-180 ksi |
| Maraging steel | Martensitic | Solution-treated and aged | Maraging-200 and -250 |
| 400 series stainless 410, 416, 422, 431 | Martensitic | Quenched and tempered | Not susceptible if tempered at 1100°F or higher |
| 15-5 PH | Martensitic | H950 to H1000 | |
| PH 13-8 Mo | Martensitic | H950 to H1000 | |
| 17-4 PH | Martensitic | H950 to H1000 | |
| AM 355 | Semi-austenitic | SCT 950 to H1000 | |

Table 5. Materials with Low Resistance to SCC

| Materials | Type | Heat Treatment | Remarks |
|---|---|---|---|
| Low-alloy steels 4130, 4140, 4340, 8740, D6AC, HY-TUF | Martensitic | Quenched and tempered | Very susceptible to SCC if tempered to 180 ksi and higher |
| Maraging | Martensitic | Solution-treated and aged | Maraging-300 |
| H-11 | Martensitic | Quenched and tempered | |
| 17-7 PH | Semi-austenitic | All heat-treatments except CH900 | |
| PH 15-7 Mo | Semi-austenitic | All heat-treatments except CH900 | |
| AM 355 | Semi-austenitic | Heat-treatments below SCT 900 | |
| 400 series stainless 410, 416, 422, 431 | Martensitic | Quenched and tempered | Very susceptible in the secondary hardening range from 500 to 1000°F |

## IV. FAILURES DUE TO SCC OR HSC ON THE TITAN III FAMILY OF VEHICLES

The Air Force Titan III Program has had difficulties with high-strength fasteners on the boosters during the past 6 or 7 years. Table 6 lists some of the fastener steels and modes of failure. Failures were all in a marine atmosphere. The precipitation-hardening steels have all been slowly replaced by the cold-worked type of A286. The 440C and H-11 were continued in service, but either their heat treatments were modified or protection by organic coatings became a requirement, or both. Type 212 was eliminated, but Type 431 was continued in service with organic coatings; long-range solutions involved substitution of A286.

These failures occurred during the early years of Titan III development despite a program of stress corrosion control. Tensile stresses (preloads) on the fasteners are now minimized to 40 percent of yield, and materials are heat-treated where possible to UTS of 160 ksi. The importance of stress level, environment, and metallurgical structure of the metal in SCC and HSC is recognized by the Program Office. Contact with dissimilar metals, the most likely source of hydrogen from corrosion, is avoided or protected against. Chemical conversion coatings and anodizing on aluminum often retard such corrosion.

NASA plans to initiate studies of service influence on fracture behavior, i.e., use of fracture mechanics concepts (Ref. 27). NASA has had a few failures by corrosion in 4330, 4340, AM 355, and 17-7PH.

Table 6. Fastener Failures on the Titan III Family of Vehicles

| Material | Hardness, UTS and/or Heat Treatment | Application | Probable Failure Mode |
|---|---|---|---|
| 15-7 Mo | $R_c$ 46 | Shear tie bolt between solid core and liquid core | SCC |
| 15-5PH | 180 to 190 ksi | Solid rocket motor frangible bolt | HSC from galvanic coupling |
| 17-4PH | H 950 | Fuel and oxidizer valve assemblies | HSC |
| 440C | $R_c$ 57 | Actuator adjustable bolt | SCC |
| H-11 | $R_c$ 52 260 ksi | Launch pad baseplate stems | HSC from galvanic coupling |
| 431 | 180 ksi | Marman clamp on hot gas cooler | SCC |
| Unitemp 212 | 180 ksi | Solid rocket motor | HSC |
| 17-4PH | $R_c$ 46; 1 hr 900°F | Pressure valve | SCC |
| 431 | 180 ksi | Solid rocket motor | HSC |

## V. THE PROMISE OF FRACTURE TOUGHNESS CRITERIA

Improvement of analysis of fracture in various environments through the use of fracture mechanics allows microscopic study of the fracture process (whether by SCC or HSC) independent of the influence of specimen geometry effects and dependent only on stress level and environment. The fracture toughness approach gives, for the first time, a quantitative knowledge of the effects of a particular environment on a steel stressed below the yield stress. Such quantitative data will be required by the designer once he learns how to use it. This method reflects the behavior of a metal in an environment that may lead to either SCC or HSC and does not differentiate between mechanisms leading to failure.

The $K_{ISCC}$ parameter, hence, indicates with good reproducibility the stress-crack-size threshold below which subcritical cracks will not propagate to a critical size leading to catastrophic failure in a gaseous, liquid or complex environment in a period of usually 500 to 1000 hours. Both $K_{IC}$ and $K_{ISCC}$ have units of ksi $\sqrt{\text{in.}}$ Both K's are also independent of specimen geometry.

Because smooth test specimens require long times for crack nucleation, Brown (Refs. 28 and 29) and others have used specimens with preexisting cracks, thus eliminating the crack initiation period during which surface films break down and pitting starts. The use of these specimens reduces the likelihood of erroneous conclusions that alloys are immune to SCC (they may not pit in the test environment, and pitting is generally prerequisite to SCC) and permits the use of fracture mechanics concepts. Brown introduced the concept of the threshold, $K_{ISCC}$. Very quickly Brown's idea became popular, and many investigations have shown the value of this approach.

The use of plane strain[4] fracture toughness criteria, i.e., $K_{IC}$ and $K_{ISCC}$, makes it possible to select fastener materials that are not susceptible

[4]The term plane strain conditions refers to the square fracture produced by SCC or HSC. Plane stress conditions would involve slant or shear fractures, which are not ordinarily observed with SCC or HSC.

to either SCC or HSC on the launch pad or in any other environment. The fracture mechanics approach can show whether a metal is affected by the stress environment and to what degree. The analysis also shows that where degradation occurs there is a threshold stress below which no SCC or HSC occurs, as shown in Figure 5. Note how severely the salt environment reduces the stress intensity factor $K_I$ (Ref. 30).

In tough alloys, failure occurs after longer time intervals. Crack propagation may be slower, and the alloy may tolerate a longer crack before fracturing. A small crack may cause SCC in a material of low toughness, whereas a larger crack may be required to fail a tougher material. The tougher material may require a longer time to fail because crack growth is slower in a tougher material and not because SCC or HSC is slower. Time to failure thus can be used as a measure of SCC growth.

Relating the environmental applied stress intensity factor $K_{ISCC}$ to the plane strain fracture toughness $K_{IC}$ permits normalization of the differences in toughness or heat treatments of alloys. The ratio $K_{ISCC}/K_{IC}$ serves as a normalizing parameter for comparison of steels and their heat treatments. Figure 6 shows the delayed fracture characteristics of 4340 steel heat-treated to various strength levels in distilled water (Ref. 31). Figure 7 shows the same data of Figure 6 normalized by use of the stress intensity ratio $K_{ISCC}/K_{IC}$.

Stress corrosion tests using precracked specimens have assumed increasing importance in the aerospace industry. These tests are useful to the designer, the engineer, and the metallurgist. A knowledge of $K_{IC}$ and $K_{ISCC}$ is important for structural design.

Distilled water and moisture in the atmosphere are seldom considered to constitute an aggressive environment, yet moisture can have a controlling influence on the fracture behavior of high-strength steels. The growth of a crack from an experimentally induced flaw (e.g., EDM-Electro-discharge-machined slot) was studied by Johnson and Willner (Ref. 32), who found relationships between the crack growth rate and the crack tip under varying

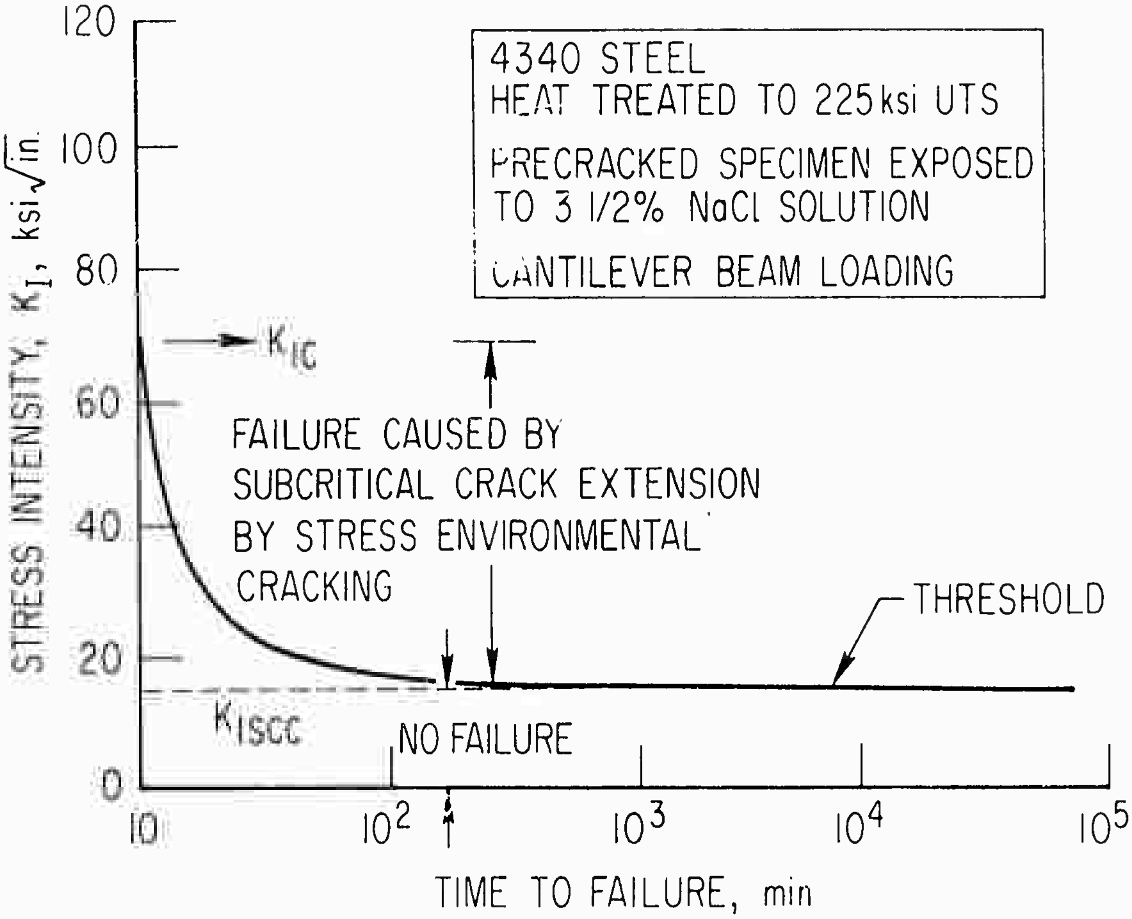


Figure 5. Typical Behavior of a High-Strength Steel in a Corrosive Environment (Ref. 3)

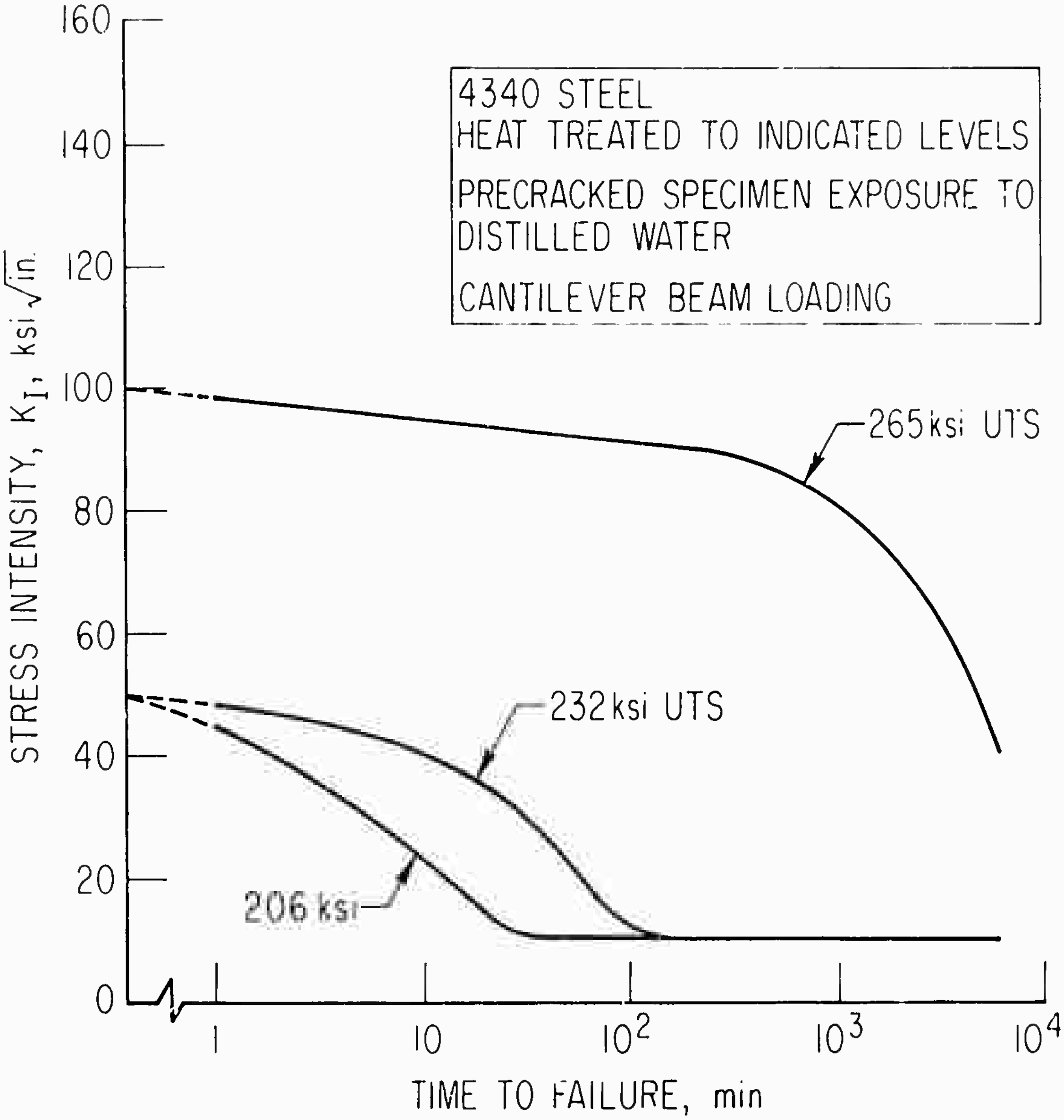


Figure 6. Delayed Fracture Characteristics of 4340 Steel at Various Strength Levels Resulting from Exposure to Distilled Water (Ref. 31)

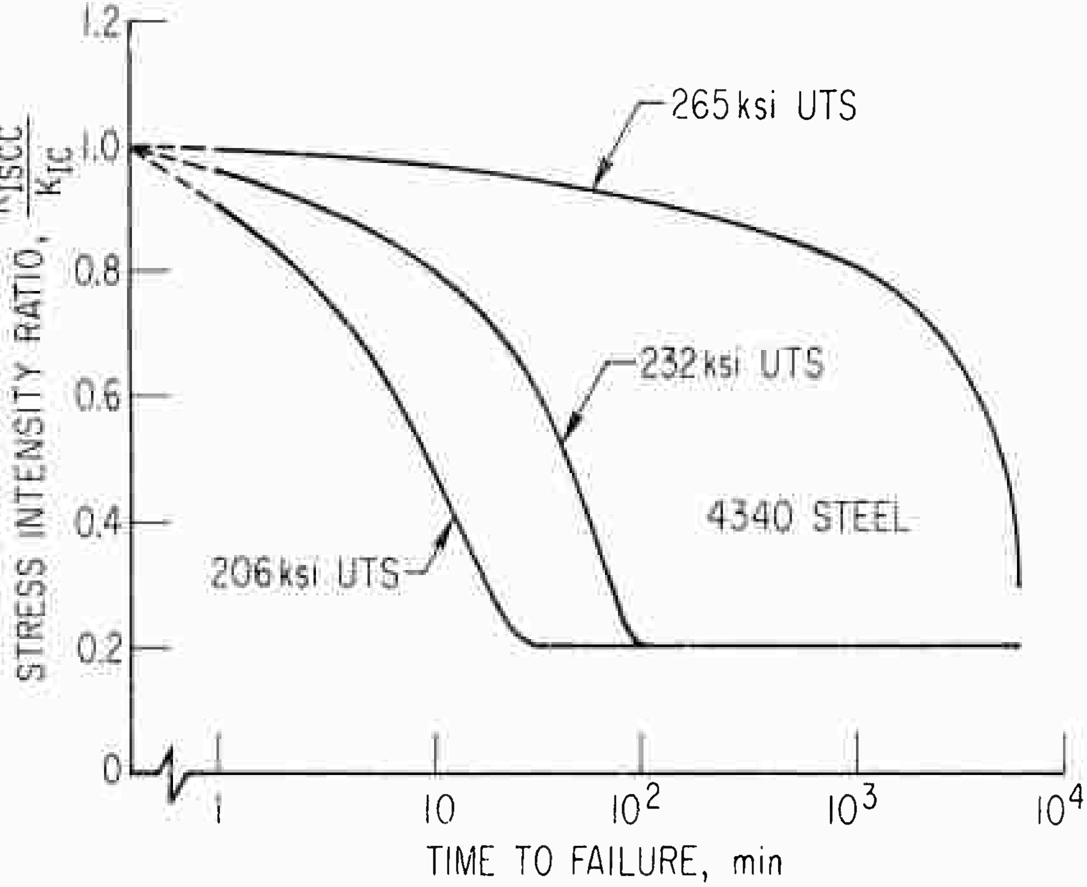


Figure 7. Data of Figure 6 Normalized by Use of the Stress Intensity Ratio (Ref. 31)

conditions of liquid water, water vapor, and temperature. The work was conducted with an H-11 steel heat-treated to a strength of 230 ksi. Water vapor had a marked effect on crack growth at constant load; crack growth changed as humidity was varied. The crack propagation in water or water vapor is consistent with crack propagation mechanisms of either SCC or HSC. It is highly probable that either mechanism can occur in high-strength steels and that the chemistry of the aqueous environment determines which mechanism is operative. In this instance, however, it is very likely that corrosion occurs on this steel and hydrogen enters the metal (Ref. 33). Hanna, Troiano, and Steigerwald (Ref. 7) have also presented evidence that HSC occurs with distilled water; the hydrogen is supplied by the cathodic reaction of a corrosion cell. In addition, the crack growth rate activation energy of 9000 cal/mole agrees fairly well with the known value for the diffusion of hydrogen in iron ($Q = 7800$) (Ref. 34), which also supports the findings of Johnson and Wilner.

Since both SCC and HSC can occur in aqueous environments, it is surprising that the operative mechanism appears to depend on the nature of the steel. Benjamin and Steigerwald (Ref. 35), using fracture toughness analysis, exposed two high-strength steels to distilled water and 1.5N and 3.0N NaCl aqueous solutions. Distilled water was found to be a more agressive environment than the salt solutions for 4340, and the reverse was true for HP-9-4. Using supplementary polarization experiments, they found that delayed failure in 4340 was the result of HSC. The behavior of the HP-9-4 steel, however, was consistent with the SCC mechanism, with anodic dissolution occurring along active paths.

The type of data obtained by fracture mechanics analysis is illustrated by the work of Freedman (Ref. 36), who obtained $K_{IC}$ and $K_{ISCC}$ data on ferrous and nickel alloys. Single-edge notched and fatigue-cracked specimens were tension-loaded in a salt solution for 1000 hr (accelerated test). Identical specimens were tension-loaded in racks exposed at the seacoast (Playa del Rey, California). Times to failure at seacoast varied from 49 to 7668 hr. Some specimens were tested for 12,843 hr without failure.

Freedman's data (Table 7) give a rating of the susceptibility of various alloys to accelerated (laboratory) and seacoast testing; the ratio $K_{ISCC}/K_{IC}$ for seawater ranks the alloys from Inconel 718 (most resistant) to sensitized Type 304 (most susceptible). There are unexplained differences in the ratio for the accelerated test, which can probably be attributed to the variability of the aggressive environments.

Additional data on the stress-corrosion properties of the precracked high-strength precipitation-hardening stainless steels were obtained by Carter (Ref. 25). These data (see Table 8) showed that the precipitation-hardening stainless steels (e.g., 17-7 PH and PH 15-7 Mo) were particularly sensitive to SCC. Most martensitic steels were very resistant, with $K_{ISCC}/K_{IC}$ very close to unity. Steels with low $K_{ISCC}$ values had low $K_{IC}$. All failures were intergranular.

Overaging was found to increase fracture toughness and stress-corrosion resistance. As might be expected, comparison of data for precracked specimens and smooth specimens revealed discrepancies.

Comparison of Freedman's data with those of Carter and co-workers is not possible because of the different alloys tested. In only two cases are the data comparable: AM355 SCT 1000 and 17-4 PH H900. There exist wide and unexplained differences in the $K_{ISCC}/K_{IC}$ ratios.

The effect of high-pressure (5000 psi) hydrogen on Inconel 718, Inconel 625, A286, AISI 347, Ti-6Al-4V and Ti-5Al-2.5Sn has been studied by fracture mechanics analysis (Refs. 37 and 38). Of the group, Inconel 718 and A286 were most resistant, while Inconel 625 was most embrittled.

Table 7. Fracture Toughness Rating of Alloys and Heat Treatments for Resistance to Saltwater Environments (Northrop Data, Ref. 36)

| Material | Heat Treatment | UTS, ksi | Seacoast Test | | Accelerated Test | |
|---|---|---|---|---|---|---|
| | | | $K_{ISCC}$ | $K_{ISCC}/K_{IC}$ | $K_{ISCC}$ | $K_{ISCC}/K_{IC}$ |
| Inconel 718[a] | 1950°F AC, 8 hr 1350° + FC to 1200°F for 24 hr | 189.6 | 106 | 0.87 | 130 | 0.98 |
| 17-4 PH[a] | H 1150 | 151.6 | 93.9 | 0.77 | 110 | 0.89 |
| AISI 304 | Annealed | 84.0 | 53.5 | 0.77 | 59.7 | 0.86 |
| 4340 | 800°F Tempered | 204.8 | 48.3 | 0.72 | 29.7 | 0.44 |
| 17-4 PH | H 900 | 202.4 | 38.5 | 0.69 | 40.3 | 0.72 |
| H-11 (AM)[b] | 1100°F Tempered | 232.6 | 39.5 | 0.62 | 23.2 | 0.24 |
| 410[a] | 1125°F Tempered | 128.8 | 52.4 | 0.55 | 49.6 | 0.52 |
| H-11 (AM)[b] | 1000°F Tempered | 300.3 | 16.7 | 0.52 | 8.6 | 0.27 |
| 18 Ni (250) | 900°F | 269.5 | 55.6 | 0.50 | 72.9 | 0.65 |
| H-11 (VM)[b] | 1000°F Tempered | | 11.4 | 0.40 | 10.8 | 0.38 |
| 4340 | 475°F Tempered | 267.2 | 13.3 | 0.29 | 11.1 | 0.24 |
| AM 355 (FH)[b] | SCT 1000 | | 33.1 | 0.28 | 50.3 | 0.42 |
| AM 355 | SCT 1000 | 169.4 | 24.5 | 0.24 | 36.7 | 0.43 |
| 410 | 650°F Tempered | 197.0 | 22.0 | 0.24 | 23.8 | 0.26 |
| AM 355 | SCT 850 | 195.9 | 10.7 | 0.22 | 24.9 | 0.52 |
| AM 355 (FH)[b] | SCT 850 | | 9.7 | 0.15 | 6.2 | 0.10 |
| AISI 304 | Sensitized 100 hr 1100°F | 83.9 | 8.5 | 0.12 | 15.2 | 0.22 |

[a] Plane strain conditions maintained only at low stress intensities. Therefore, values are approximate. True plane strain $K_{ISCC}$ could not be obtained.

[b] AM = air melt, VM = vacuum melt, FH = fully hardened.

Table 8. Fracture Toughness Rating of Alloys and Heat Treatments for Resistance to Saltwater Environments (Boeing Data, Ref. 25)

| Material | Heat Treatment | UTS, ksi | $K_{ISCC}/K_{Ic}$ |
|---|---|---|---|
| AM 355 | SCT 1000 | 178.0 | 1.00 |
| AM 355 | SCT 1000 Modified | 173.4 | 1.00 |
| AM 364 | H 950 | 191.5 | 1.00 |
| 17-4 PH | H 900 | 194.6 | 1.00 |
| 17-4 PH | H 1000 | 162.2 | 1.00 |
| 15-5 PH (AM)[a] | H 1000 | 161.6 | 1.00 |
| 15.5 PH (VM)[a] | H 1000 | 162.9 | 1.00 |
| PH 13-8 Mo | H 950 | 225.1 | 1.00 |
| Custom 455 | H 950 | 247.0 | 1.00 |
| 15-5 PH (AM)[a] | H 900 | 195.7 | 0.83 |
| AM 362 | H 1000 | 178.9 | 0.77 |
| 15.5 PH (VM)[a] | H 900 | 191.5 | 0.75 |
| AM 364 | H 850 | 188.7 | 0.71 |
| 17.7 PH | RH 950 | 186.5 | 0.59 |
| PH 15-7 Mo | TH 1050 | 178.2 | 0.55 |
| AM 355 | SCT 850 | 213.5 | 0.55 |
| PH 15-7 Mo | RH 950 | 219.4 | 0.44 |
| AM 362 | H 900 | 200.5 | 0.41 |
| 17.7 PH | TH 1050 | 197.2 | 0.41 |

[a] AM = air melt, VM = vacuum melt.

Table 9. Results of Sustained-Load Experiments with Notched Specimens of Various Ultra-High-Strength Steels Exposed to a 5% Salt-Fog Atmosphere (Ref. 51)

| Steel | UTS Range, ksi | Applied Stress, ksi[a] | Type of Coating | Number of Failures in 1000 hr/Number of Specimens Tested |
|---|---|---|---|---|
| 4340[b] | 260-280 | 163 | Not plated | 3/3 |
| 4340[b] | 260-280 | 163 | Low H Cd plated | 3/3 |
| 4340[c] | 260-280 | 163 | Not plated | 3/3 |
| 4340 | 260-280 | 163 | Low H Cd plated | 3/3 |
| 4340 | 180-200 | 120 | Not plated | 0/3 |
| 4340 | 180-200 | 120 | Vacuum-deposited Cd | 0/3 |
| 4330M | 220-240 | 142 | Not plated | 3/3 |
| 4330M | 220-240 | 142 | Low H Cd plated | 2/3 |
| H-11 | 280-300 | 175 | Not plated | 3/3 |
| H-11 | 280-300 | 175 | Low H Cd plated | 2/3 |
| H-11 | 280-300 | 175 | Ni-Cd plated | 2/3 |
| H-11 | 260-280 | 163 | Not plated | 3/3 |
| H-11 | 260-280 | 163 | Low H Cd plated | 0/3 |
| H-11 | 260-280 | 163 | Ni-Cd plated | 0/3 |
| D6ac | 280-300 | 175 | Not plated | 3/3 |
| D6ac | 280-300 | 175 | Vacuum-deposited Cd | 3/3 |
| D6ac | 260-280 | 163 | Not plated | 3/3 |
| D6ac | 260-280 | 163 | Vacuum-deposited Cd | 2/3 |
| D6ac | 220-240 | 142 | Not plated | 3/3 |
| D6ac | 220-240 | 142 | Vacuum-deposited Cd | 3/3 |
| D6ac | 220-240 | 142 | Ni-Cd plated | 0/3 |
| HP-9-4-45 | 260-280 M[d] | 163 | Not plated | 3/3 |
| HP-9-4-45 | 260-280 M[d] | 163 | Vacuum-deposited Cd | 3/3 |
| HP-9-4-45 | 260-280 B[e] | 163 | Not plated | 3/3 |
| HP-9-4-45 | 260-280 B[e] | 163 | Vacuum-deposited Cd | 3/3 |
| C-455 | 220-240 | 142 | Not plated | 0/3 |
| C-455 | 220-240 | 142 | Vacuum-deposited Cd | 3/3 |
| C-455 | 220-240 | 142 | Ni-Cd plated | 0/3 |
| AFC-77 | 240-260 | 142 | Not plated | 2/3 |
| AFC-77 | 240-260 | 142 | Vacuum-deposited Cd | 3/3 |
| 18Ni (280) | 280-300 | 175 | Not plated | 3/3 |
| maraging | 280-300 | 175 | Vacuum-deposited Cd | 3/3 |
| | 280-300 | 175 | Ni-Cd plated | 1/3 |
| 18Ni (250) | 250-270 | 163 | Not plated | 0/3 |
| maraging | 250-270 | 163 | Vacuum-deposited Cd | 0/3 |
| | 250-270 | 163 | Ni-Cd plated | 0/3 |

[a]The applied stress was equivalent to about 75% of the design yield strengths of the steels, except for the maraging steels.

[b]Air melted.

[c]Vacuum melted.

[d]Martensitic heat treatment.

[e]Bainitic heat treatment.

## VI. RECOMMENDATIONS

Two major problems related to SCC and HSC confront the aerospace industry: (1) prevention of SCC and HSC and (2) test standardization, data accumulation, and dissemination of information.

### A. PREVENTION OF SCC AND HSC

There are some obvious practical approaches to the problem of failed fasteners by SCC and HSC. The first is the use of alternative materials. There are materials with good resistance to SCC. On the basis of the fracture toughness criteria, $K_{ISCC}$, and the ratio $K_{ISCC}/K_{IC}$, tempered with experience, a selection could be made. Unfortunately, fracture toughness criteria are only now being collected and not all fastener materials have been tested. However, there are some highly corrosion-resistant materials of the stainless steel type available, e.g., A286, A286 CW, Inconel 718, and Inconel 718 CW.

The second obvious solution is to keep the agressive environment or the hydrogen source away from the steel. Although aerospace engineers shy away from coatings, platings of cadmium or aluminum may be helpful on low-alloy steel martensites. Extreme care in electroplating and required subsequent baking must be exercised at high strength levels to prevent HSC. In some aerospace applications, organic coatings, paints, Lock-tite, Lock-safe, greases, or even baked-on solid lubricants can protect against the environments. Torquing and retorquing on the bolts can remove these types of coatings, and reapplication of the protection is then required.

The resistance to environmental cracking (5% salt fog) of ten high-strength steels, with and without cadmium or cadmium-nickel coatings, was studied by Lauchner (Ref. 39); the results are given in Table 9. Some steels, AISI 4340 (180-200 ksi UTS), Custom-455 (220-240 ksi UTS), and 18 Ni (250 ksi UTS), had good resistance to SCC in this environment without

coatings. Note the superiority of the cadmium-nickel coating to the other types of cadmium coatings (low hydrogen plated and vacuum deposited).

A less obvious solution to the problem is the use of designs that eliminate or minimize factors promoting SCC and HSC. One should, for instance, avoid crevices, deep recesses, sharp corners, notches of any kind, and dissimilar metals unless one metal is insulated from the other.

In any design in which new alloys are to be tried and new environments experienced, it is highly recommended that fracture toughness tests be conducted to ascertain the possibility of some susceptibility to degradation, if not complete failure.

## B DATA COLLECTION AND TEST STANDARDIZATION

There is a need for standardization of fracture toughness tests using the precracked specimens. The ASTM already has a tentative specification on testing (Ref. 3). Without standardization, the available data have limited usefulness in material selection or design. A standard test must be in existence long enough that sufficient data can be accumulated for statistical study.

The accumulated data should be compiled into usable form by industry, the metallurgical profession, a government agency, or a technical society.

# VII. CONCLUSIONS

The current technology of high-strength fasteners in aerospace applications has been appraised.

While there is a distinct difference between SCC and HSC phenomena on the laboratory scale, it is difficult, if not impossible, to differentiate between the two mechanisms in the field. Corrosion theory is not sufficiently advanced to predict dangerous stress-environment-structure combinations that could lead to failure.

The high-strength fasteners that occasionally fail in service can be divided into three types of categories: (1) by [illegible] level, (2) by metallurgical type, and (3) by relative susceptibility to [illegible] conditions or marine atmospheres.

Examples of failures on the Titan III [illegible] vehicles illustrate the nature of the problem.

Fracture toughness analysis offers the best hope of obtaining data on SCC or HSC. The analysis does not differentiate between [illegible]. The use of plane-strain fracture toughness $K_{Ic}$ and stress corrosion threshold $K_{ISCC}$ criteria offers promise of selecting [illegible] that are not susceptible to SCC or HSC failures. The $K_{Ic}$ or $K_{ISCC}$ [illegible] are becoming more meaningful to the design [illegible] area, because these measures of [illegible] have [illegible] performance of a structure.

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